

Be Stars as Seen Through Telescopes in Survey Mode (I)

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Abstract. In spite of the almost all-encompassing variability of Be stars, surveys play a steadily increasing role in complementing the insights gained from single-star studies. The definition of classical Be stars as recently augmented by Rivinius, Carciofi, and Martayan (2013) enables unambiguous identification of Be stars in a much increased range of observations. Results of targeted surveys are briefly reviewed for the effects of metallicity, binarity, and evolution. It still remains to be seen whether Be stars are safe benchmarks for the calibration of evolutionary models with rapid rotation.

1. Introduction

Single-star studies (e.g., Štefl et al. 2003a,b; Maintz et al. 2003; Štefl et al. 2009; Carciofi et al. 2009) perhaps still come close to the maximum of what observations can currently disclose about (sometimes so-called classical) Be stars. But the need for multi-wavelength multi-technique monitoring campaigns renders such efforts expensive, the necessity of closely contemporaneous observations can be a major logistical challenge, and the representativeness of the results can be questionable.

At least as a complementary effort, surveys are very important. However, the strong irregular variability of key observables makes it difficult to combine data from different epochs. Biases abound, and often surveys are still too exiguous to unveil correlations. This situation could be alleviated by efforts to combine different surveys in metadatabases. A special statistical pitfall arises from the unfortunate coincidence that the fraction of Be stars is highest around spectral type B2, where the Balmer emission is strongest and the central stars are intrinsically bright.

2. Surveys

Be stars are young so that searches should focus on young clusters and star-forming galaxies. Less straightforward is the choice of search criteria.

2.1. How to identify Be stars?

For at least one generation, the following definition of Be stars (Jaschek, Slettebak, and Jaschek 1981; Collins 1987) was widely used: “a non-supergiant star whose spectrum

has, or had at some time, one or more hydrogen / Balmer lines in emission.” The strict avoidance of any interpretative risk leaves little leeway but also leads to confusion with Herbig Be stars, B[e] stars, stars with magnetospheres, mass exchanging binaries, and even the meant-to-be-excluded supergiants.

Recently, Rivinius, Carciofi, and Martayan (2013) proposed to add (i) very rapid rotation, (ii) nonradial pulsation, (iii) the absence of magnetic fields, and (iv) the irregular ejection (by some unknown process) of matter, from which a (v) viscous and (vi) dust-free (vii) disk with (viii) Keplerian rotation is formed. This opens up eight more channels for the selection of candidate Be stars, of which, however, viscosity and the absence of magnetic fields and dust do not seem suited for positive detections in survey work. Obviously, this approach introduces additional options for false positives (also depending on observing technique). Examples include:

- Rapid rotation: Bn stars
- Nonradial pulsation: SPB stars, surface inhomogeneities, magnetospheres
- Ejection of matter (when observed photometrically): gravitational lensing, eclipses
- Disk: magnetospheres, interstellar matter, accretion disks

But since the false positives are mostly rather different from each other, recursive application of the criteria will lead to the confirmation or rejection of the Be-star nature with quickly increasing probability.

In addition to the above, Be stars display characteristic light curves (e.g., Menickent et al. 2002). While it is unknown whether certain photometric behaviors are necessarily associated with the Be status of a star, shapes of light curves can serve as an effective filter.

2.2. Available surveys and future survey facilities

A list will be submitted to the Web site of the IAU Working Group on Active B Stars¹.

3. Metallicity effects

Metallicity is perhaps the most important parameter targeted by observations of Be stars beyond the solar neighborhood. Low metallicity favors rapid stellar rotation in two ways: (1) Stars are more compact, and (2) radiative wind driving is less effective so that stars retain more of their primordial angular momentum. In agreement with this expectation, Martayan et al. (2007) and Martayan, Baade, and Fabregat (2010) found that the specific frequency of Be stars and their rotation rates increase from Milky Way (MW) to LMC and further to SMC. However, an only slightly closer look reveals that in all three galaxies peak cluster-to-cluster variations are not any smaller. Therefore, there must be another parameter ranking roughly at par with metallicity. In photometry, metallicity effects are often degenerate with the ones of age. In fact, Fig. 7 in Iqbal and Keller (2013) is strongly suggestive of metallicity and age being of comparable relevance for the abundance of Be stars (see also Maeder, Grebel, and Mermilliod 1999).

The interpretation of differences in the frequencies of Be stars in different environments depends also on the understanding of metallicity effects on the appearance

¹<http://activestars.iag.usp.br/>

of their disks, where the name-giving emission lines form. On the empirical side Wisniewski et al. (2007) ‘speculate’ that, at SMC-level metallicity, disks are either smaller or hotter than in the MW.

Models do not yet come in as firm arbiters. Halonen and Jones (2013) conclude that metallicity-based differences in heating due to absorption and radiative cooling roughly cancel out. Be star disks would only be slightly sensitive to metal abundances. By contrast, Ahmed and Sigut (2012) calculate that, at identical stellar effective temperature, disks with SMC abundances should be hotter by several thousand Kelvin. Their models crudely reproduce the distribution of H α equivalent widths measured by Martayan et al. (2007) in MW and SMC stars.

4. Binarity

Recent surveys have drastically increased the multiplicity estimates for massive stars. While Sana et al. (2012) focus exclusively on O stars, the study by Chini et al. (2012) shows that across the mass range of Be stars the fraction of multiple stars varies by a factor of a few. Therefore, it is not obvious whether Be stars as a group are or are not globally affected. Snap-shot surveys (e.g., Nasserri et al. 2013) do not find systematic differences between Be and other B stars, while short-period systems seem to be underrepresented among Be stars and there is also no tangible evidence that passages of a companion trigger mass-loss events. Theoretical expectations (Waters et al. 1989) that many Be stars should have white-dwarf companions have not received observational confirmation (Peters et al. 1992). But there are three or four Be+sdO systems known (cf. Peters et al. 2013). Mass transfer from the progenitor of the sdO star has probably spun up the Be star and so laid the foundation to the occurrence of the Be phenomenon (for a description see Rivinius, Carciofi, and Martayan 2013) in these objects. Because of the low radial-velocity amplitudes and the difficulty of obtaining UV-to-optical SED’s it is not easy to estimate how statistically important this sub-population is. Significant variability in radial velocity of HeII 4686 seems the best symptom to search for in order to increase the sample.

All in all, the Be phenomenon does have a contribution from binarity. But the current number and properties of Be stars with a companion do not indicate that the binary path to today’s Be stars is of elevated importance. This may not have been true, though, at the time of their formation.

For instance, B stars in high-mass X-ray binaries seem to be fairly normal Be stars, and they could be the surviving tip of the iceberg with many others lost in supernova explosions. However, in that case, one would expect significantly more high-velocity Be stars, which is not the case. Rapid rotation could also be due to early mergers. Again, observations do not match predictions: Peculiar abundances are not common in Be stars (Rivinius, Martayan, and Baade, these proceedings), and of all early-type stars studied, Be stars seem to be the least magnetic (e.g., Wade, these proceedings). Therefore, the Be phenomenon is not a general binary phenomenon.

5. Evolution of Be stars: models

Mastering the challenges of extreme rotation is still an ongoing process in the development of stellar evolutionary models. Three questions play a dominant role: (1) What is

different at fast rotation? (2) Which predictions can observations verify? (3) How can single stars attain, and retain, surface rotation rates as high as observed in Be stars?

The basic effects are well known (Maeder and Meynet 2012): The rotationally reduced equatorial gravity lowers the effective temperature from pole to equator (von Zeipel 1924). This causes a breakdown of the thermal equilibrium, which induces meridional circulation, and differential rotation adds horizontal turbulence and shear. Their combination has a number of consequences:

- The radial mixing is enhanced.
- This increases the effectively available amount of fuel and so extends the lifetime.
- At the same time, core and envelope are more strongly coupled.
- Angular momentum is radially transported and the surface rotation accelerated.
- Surface abundances (especially of helium and nitrogen) are enhanced.
- If and where there is a radiative wind, the mass loss is strengthened.

Because all Be stars are very fast rotators and readily identified, models often aim at reproducing the observed properties of Be stars. But Be stars are special:

- o Be and Bn stars have different pulsational properties.
- o Be stars suffer significant episodic mass loss. Bn stars do not.
- o Be stars show marked star-to-star differences in variability and disk properties.
- o Be stars may be particularly little affected by binarity.
- o Be stars have less relevant large-scale magnetic fields than other early-type stars.

That is, Be stars may not be good benchmarks for the calibration of evolutionary models with fast rotation. This needs to be kept in mind throughout the next section, which relies entirely on Be stars.

6. Evolution of Be stars: observational verification

Perhaps, the primary result/objective of stellar-evolution models are evolutionary tracks in the HR diagram. Because the rotation-induced differences are mostly relatively subtle (Granada et al. 2013), comparison to observations requires combining data from many clusters, all of which have different ages, metallicity, foreground reddening, etc. Moreover, the transformation from the observational to the theoretical HRD requires knowledge of the inclination angle of the rotation axis of each star. In summary, evolutionary tracks offer only moderately promising verification opportunities.

A similarly challenging verification channel is the comparison of the numbers of ultra-rapidly rotating stars. Models (Granada et al. 2013) predict a clear variation with age - but only in a range, where reliable measurements can only be done in intensive-care mode for individual stars.

The evolutionary core-to-envelope angular-momentum transfer process is slow, and it is fastest in the high-rotation regime (Granada et al. 2013), where the path to meaningful statistics is long and laborious. However, current models simply start in a fully convective state upon arrival on the ZAMS. Inclusion of more realistic star-formation models may lead to more differentiated results.

The clearest finger print of stellar evolution should be imposed on the surface abundance patterns. For instance, Granada et al. (2013) expect rotation to increase the nitrogen surface abundance of a $9 M_{\odot}$ SMC star by up to a factor of 500. Surprisingly, Dunstall et al. (2011) observed no difference between Be and B stars in both LMC and SMC. Accordingly, they concluded that any critical-rotation phase must be short. However, this seems at variance with reports by Martayan et al. (2007) and others that Be stars already exist as such in the first half of their ZAMS life span. Taken at face value, this would mean that Be stars are not critical rotators. An in-depth investigation of this issue appears critically needed.

Somewhat surprisingly, observations of late evolutionary stages of stars with initial masses matching the ones of B stars do not call for Be stars as progenitors. The only model based on rapid rotation is the collapsar model by MacFadyen and Woosley (1999), which, however, would only be applicable to Be stars with an initial mass of more than $15 M_{\odot}$. Martayan et al. (2010b) suggested that the number of high-mass Be stars in the SMC, scaled up to the Universe, could account for the observed number of gamma-ray bursts.

7. Initial rotation and its role in the formation of Be stars

Even if Be stars do not form with rotation rates compatible with the ones observed later, there are at least four mechanisms that have been proposed to bridge such a putative gap and lift stars to the high-rotation regime:

- Merger with a companion
- Mass and angular-momentum transfer from a companion
- Angular-momentum transport from the shrinking core by meridional circulation
- Angular-momentum transport from the shrinking core by nonradial pulsation modes (Neiner et al. 2013)

However, the single-star cases still require a significant primordial reservoir of angular momentum.

In fact, Martayan et al. (2007) find that Be stars arrive on the ZAMS rotating more rapidly than B stars in general. That is, their Be nature may be innate, not acquired. Furthermore, Be stars are mostly quasi-single.

This motivates the question whether Be stars can form through a channel that does not share angular momentum with a companion. Can very rapid rotation enable contracting gas clouds to shed excess angular momentum without fragmentation? In a way similar to jets in AGN, microquasars, and collapsars (or to Herbig Haro objects)?

The lower mass limit of Be stars is probably set by the lack of ionizing photons. The high-mass limit is usually argued to result from the onset of strong winds that prevent the formation of disks. But it is probably necessary to add that strong mass loss also reduces surface rotation rates, which further quenches any Be attitudes. On the other hand, more massive stars are more likely to be multiple. If Be stars do not follow this rule, could it, therefore, be that the onset of fragmentation plays an additional role?

8. Selected conclusions

- Mergers of catalogs would be extremely helpful. Given the strong variability on all timescales, the epochs of the observations must be included. This has repercussions on the complexity of the database required to support meaningful queries and other operations. But the effort would be well spent.
- Degeneracies between metallicity and age require caution in the analysis of photometric data.
- As long as it is not confirmed that Be stars are the vanilla type of rapidly rotating B stars, any investigation of the effects of rapid rotation should include some rapidly rotating B stars without emission lines (Bn stars) for comparison.
- The triangle in parameter space between "rapidly rotating", "quasi-single", and "magnetic field-free" may be worthwhile exploring for insights into the formation of Be stars.

This paper is complemented by Rivinius, Martayan, and Baade (these proceedings).

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